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# EIC Detector R&D
# Progress Report

**Project ID:** eRD2
**Project Name:** Magnetic Field Cloaking Device
**Period reported:** from **July 2016** to **December 2016**
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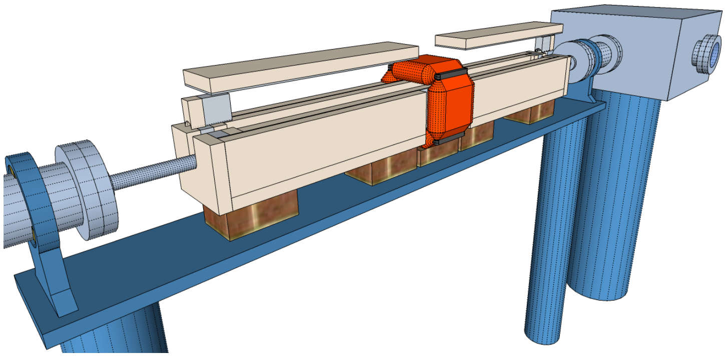
**Abstract**

The Electron Ion Collider (EIC) will collide electrons and protons/ions with very different momenta. Such collisions will generate a large number of final state particles that travel at high pseudorapidities. The momentum resolution for charged particles generally scales with the bending of these particles in a magnetic field, and thus with the magnetic field component perpendicular to their trajectories. Therefore, a magnetic field oriented transversely to the beam line could significantly improve the momentum resolution for particles at high pseudorapidities over using only the fringe field of a solenoid. However, the collider beam has to be shielded from transverse fields to avoid deflection and depolarization. This project aims at demonstrating the viability of a magnetic field cloak (consisting of a superconducting cylinder surrounded by a ferromagnetic cylinder) to create a field free tunnel for an accelerator beam through a transverse magnetic field without disturbing the field outside of it.



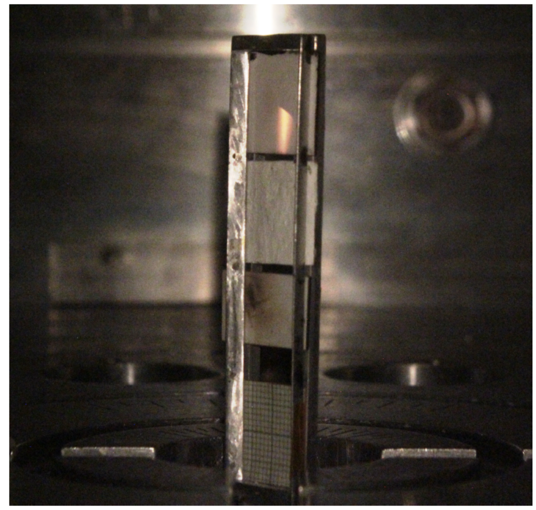


Figure 1: (left) Beam test setup at BNL with 1" OD tube connecting to the 4"OD BNL Van de Graaff beam line, aluminum/styrofoam box for liquid nitrogen, dipole magnet, and target chamber. (right) Three phosphorous screens inside the target chamber with the beam spot visible on the top one. The bottom rectangle is our position calibration grid with 0.1" spacing.

# Objectives and Achievements

For this reporting period, we planned to:

1. Demonstrate the shielding of the BNL Van de Graaff beam from a transverse magnetic field using a 1.3 m long superconductor shield made from two layers of 46 mm wide AMSC high-temperature superconductor wire insert.

2. Measure the magnetic field shielding performance of a superconducting cylinder consisting of two half-shells (each fabricated from 45 layers of 46 mm wide AMSC high-temperature superconductor wire insert) with fields up to about 0.5 T at liquid nitrogen temperature.

3. Demonstrate magnetic field cloaking with a cloak prototype (superconducting cylinder surrounded by an epoxy-steel ferromagnet cylinder) at fields up to about 0.5 T at liquid nitrogen temperature.

We have achieved all three objectives and this section presents our preliminary results.

### Shielding test with Tandem Van de Graaff beam at BNL

As described in our previous report, we have fabricated a beam shield prototype from a 60" long, 1" OD stainless steel tube which directly connects to the vacuum pipe of a beam line. Two 40" long layers of 46 mm wide AMSC superconductor wire insert attached to this tube form the actual superconductor shield. We cool the superconductor with an external liquid nitrogen bath contained inside an aluminum box with styrofoam cover. The shield is placed centered inside a dipole magnet that generates a transverse magnetic field. Figure 1 (left) shows the beam test setup.

We have measured the deflection of the BNL Van de Graaf beam (two beam species: lithium-7 and oxygen-16) as a function of the dipole field both with and without the superconducting shield. Figure 2 shows that the shield significantly reduces the beam deflection. This illustrates that our

2-layer superconductor cylinder successfully shields the beam from most of the dipole field up to about 40 mT.

### Shielding and cloaking tests with MRI Magnet at ANL

The High Energy Physics Division at Argonne National Lab (ANL) offered us to use their MRI magnet to test our magnetic field cloak prototype. The magnet provides a large bore (68 cm diameter) and a very homogenous field up to 4 T.

Figure 3 (left) shows the magnetic permeability of four epoxy-steel cylinder prototypes at magnetic fields up to 0.5 T field in the MRI magnet. While the magnetic permeability keeps decreasing with increasing fields, it does not fully saturate or become 1 in this field range. This is crucial for the cloak to work. The horizontal lines indicate the calculated ideal magnetic permeability for cloaking with superconductor plus ferromagnet (given the dimensions of our prototype) and the permeability at which we observed best cloaking at 40 mT field. We are still investigating the cause for this discrepancy. Possible reasons include imperfections in the geometry of our cloak prototype, as well as the intrinsic magnetic permeability of the superconductor wire substrate.

We used our 4.5" long, 1" outer diameter superconductor shield fabricated from 45 layers of laminated AMSC superconductor wire insert for the tests at ANL. Figure 3 (right) shows the magnetic flux measured in the center of this superconductor cylinder (cooled in a liquid nitrogen bath) as a function of the MRI field. This cylinder shields more than 99 % of the external field up to a field of about 450 mT.

To demonstrate magnetic field cloaking in the MRI magnet, we measured the magnetic flux in the direction of the MRI axis at various positions along a measurement line just outside the superconductor and outside the full cloak (superconductor plus ferromagnet cylinder) at a nominal MRI field of about 450 mT. Figure 4 shows our cloak prototype and these measurements. Adding the ferromagnet cylinder significantly reduces the amplitude of the field distortion caused by the superconductor shield: At a nominal MRI field of 446 mT, the superconductor alone causes field distortions with an amplitude of about 16% of the MRI field, while the distortions near the cloak are only about 2% of the MRI field. Further tuning the permeability of the ferromagnet and improving the fabrication of the superconductor cylinder could further reduce this residual distortion.

## Future

We have completed the key measurements we planned to do within this EIC R&D project. Our results demonstrate the feasibility of using a magnetic field cloak for collider-based applications, like experiments at the EIC and other future facilities, with fields up to about 0.5 T. Such a cloak can be built using the procedures we have established within this project. We have not found any intrinsic limitation that would prevent using such a cloak at higher fields.

Beyond the scope of this EIC R&D project, we plan to collaborate with BNL CAD / Magnet Division to devise a technical design of how a magnetic field cloak could benefit and integrate into an EIC experiment.

## Manpower

The progress documented in this report was achieved by a group of 15 Stony Brook undergraduate students working part-time. During the summer months, three of these undergraduate students were

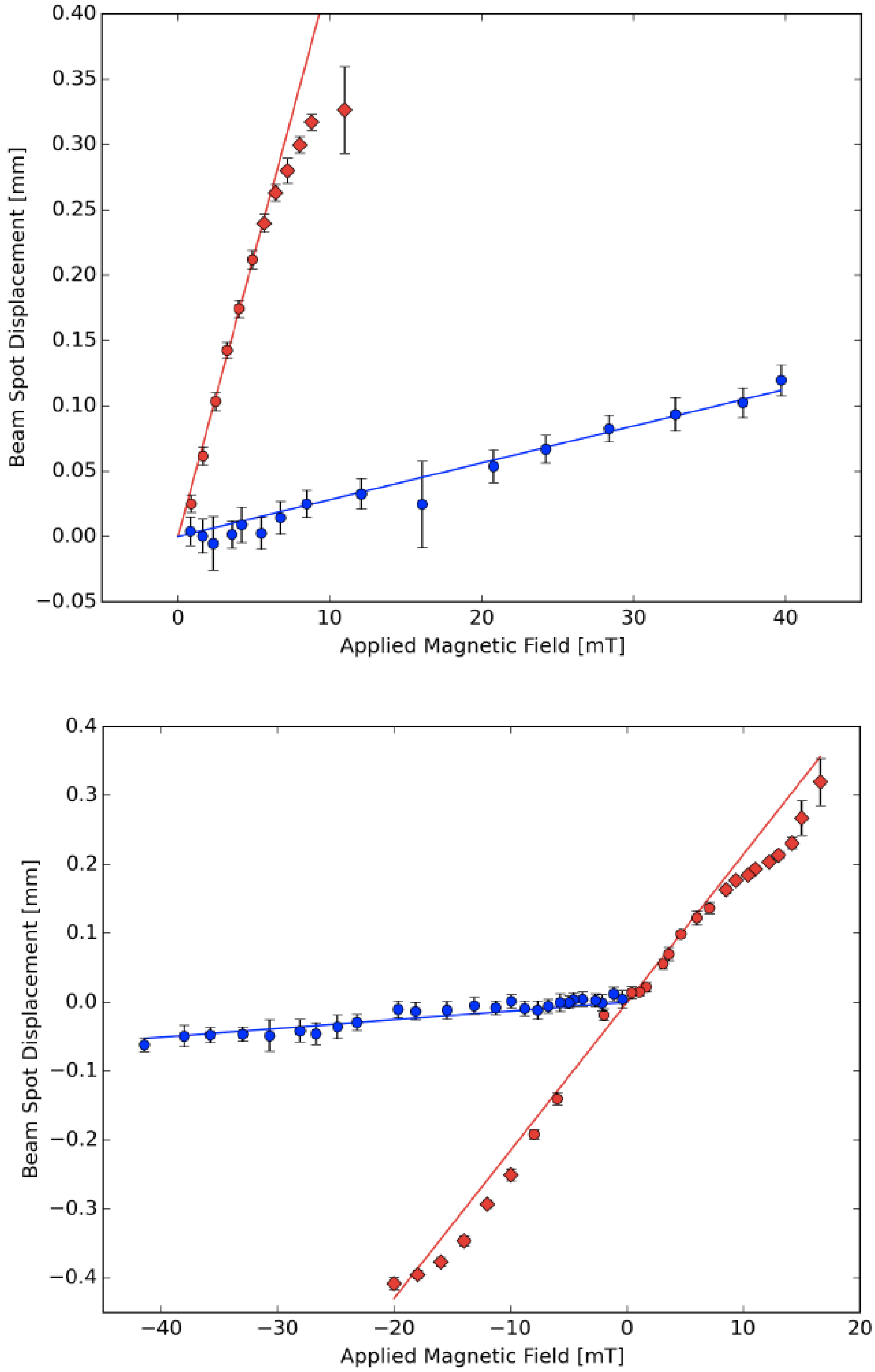



Figure 2: Preliminary results of beam displacement measurements for lithium-7 (top) and oxygen-16 (bottom). Measurements without the superconducting shield (i.e. superconductor at room temperature) are shown in red; measurements with the shield (i.e. superconductor at liquid nitrogen temperature) are shown in blue. The lines are linear fits to the beam displacement. Diamonds indicate data points that are excluded from this fit because part of the beam is being deflected off the screen, resulting in the downward skewing of the measured displacements.

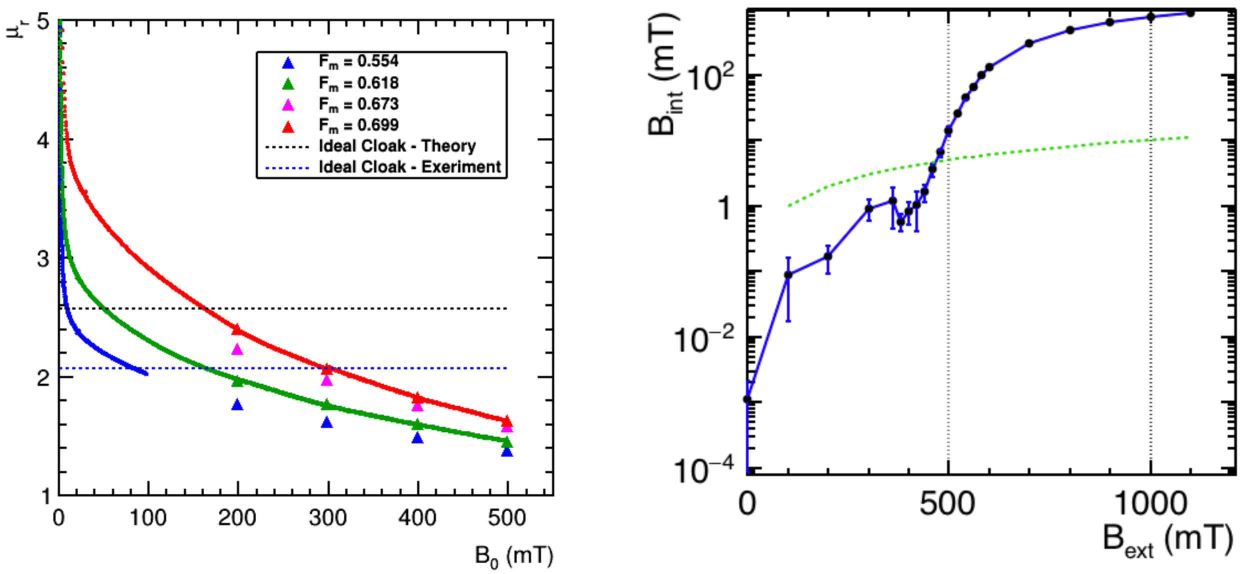



Figure 3: (left) The magnetic permeability $\mu_r$ of four different epoxy-steel ferromagnet cylinders with different steel powder fractions as a function of the nominal MRI field $B_0$. (right) Magnetic flux $B_{int}$ in the center of the 45 layer superconductor shield at liquid nitrogen temperature as a function of the nominal MRI field $B_{ext}$. The dashed green line indicates $B_{int} = 0.01 \cdot B_{ext}$.

supported with EIC R&D funds. A Stony Brook master student supported the measurements at BNL and ANL. In addition, one Stony Brook faculty spent about 50% time training and supervising students and coordinating activities. The local staffs at the BNL Tandem Van de Graaff and the ANL MRI Magnet greatly supported our measurements at the respective facilities.

## External Funding


No external funding was obtained for this project. All results presented in this report have been accomplished with EIC R&D funds only.


## Publications

- We are working towards publishing our results in *Nuclear Instruments and Methods in Physics Research, Section A*.
- Kyle G. Capobianco-Hogan et al., *Magnetic cloaking of charged particle beams*, in Proc. 2nd North American Particle Accelerator Conf. (NA-PAC'16), Chicago, IL, USA, Oct. 2016, paper TUPOB43 (submitted for publication).
- Raphael Cervantes, *A Compact Magnetic Field Cloaking Device*, MSI thesis, Stony Brook University, August 2015.

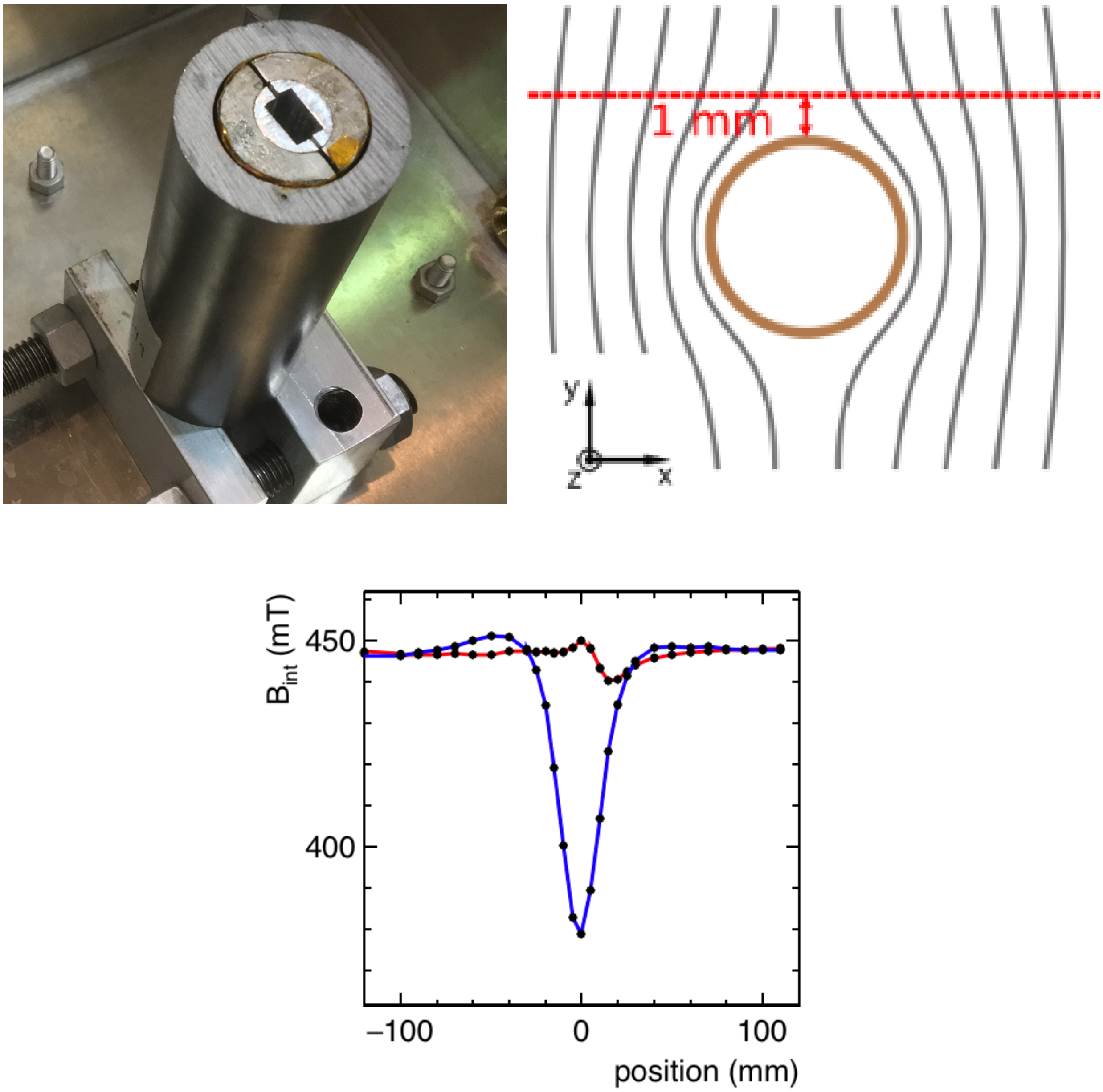



Figure 4: (top left) Our cloak prototype with 45 layer laminated superconductor shield supported by its aluminum core and surrounded by an epoxy-steel ferromagnet cylinder. (top right) Magnetic field lines (grey) and measurement line (red) along the outside of the superconductor (brown). (bottom) Magnetic flux in the direction of the MRI axis at various positions along the measurement line outside the superconductor alone (blue) and outside the cloak, i.e. superconductor plus ferromagnet cylinder (red).